

What we Think we Know about Ventilation

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Abstract

The amount of outdoor air ventilation in buildings is one of the most important determinants of indoor air quality, but many critical questions and misunderstandings exist. First, given the importance of ventilation, how well do we know how much outdoor air is even needed in buildings? While research has been done on ventilation and odour perception and on ventilation and symptom prevalence, is it adequate to support the ventilation requirements in our standards and regulations? While this research and many years of designing and operating buildings have been used to develop ventilation requirements in standards and regulations, these requirements treat all buildings the same. Can we provide understandable and practical ventilation requirements that address the tremendous variability in buildings and occupants? While much time and effort is spent developing and debating ventilation requirements, compliance with these requirements in design and ultimately operation is rarely given the attention that it deserves. Addressing actual ventilation performance in buildings requires measurement, which is more difficult to conduct in the field than often realized and is too often omitted from building management practice as well as indoor air quality research. When ventilation rates are measured, the results often reveal significant gaps between design intent and actual performance, which can have serious implications for both indoor air quality and energy. Given the importance of ventilation, the research that has been done and the many questions that remain, it is reasonable to ask how much we really know about ventilation.

Key words: Airflow, Building codes, Indoor Air Quality, Measurement, Regulation, Standards, Ventilation.

1. Introduction

Outdoor air ventilation rates are important in buildings as they impact both indoor air quality (IAQ), by determining indoor contaminant concentrations, and energy consumed for heating and cooling. While the importance of ventilation is undeniable, many critical questions exist regarding how much outdoor air should be provided to building occupants and how to achieve these rates in practice. However many of these questions have not received the attention they merit in the building and indoor air quality communities. For example, in the area of indoor air quality research, too many studies of indoor contaminant concentrations fail to include ventilation rate measurements or to even consider ventilation impacts on concentration. The result is often only a “snapshot” of concentration without any understanding of the potential range and the extent to which ventilation determines that range.

This paper discusses questions regarding building ventilation and ventilation requirements, including the science behind ventilation requirements in standards and regulations and how building and

system design, operation and maintenance determine whether or not these requirements are met in practice. The paper begins with a discussion of the scientific bases for ventilation requirements. While research results exist to support existing ventilation requirements, they are not complete in terms of building and space types, occupant characteristics, contaminant sources, and other factors. At the same time, there is a wealth of experience in designing and operating buildings that could be a source of data on how indoor air quality conditions and occupant responses are impacted by building ventilation rates. However, little research has been done to simultaneously examine these conditions, responses and rates in the wide variety of buildings that exist. Based on the limited understanding we have from the science and the field experience that has been digested, standards and regulations need to be written with requirements for outdoor air ventilation. How sound are the rationales behind these values, and should they be determined differently? Can the “one-size-fits-all” approach of ventilation requirements in L/s per person or m² of floor area be expected to handle the wide range of occupancies, activities and materials

that exist in buildings? Should our standards instead employ approaches that consider a building's unique characteristics?

Regardless of the bases of existing ventilation standards and regulations, buildings are designed and (ideally) operated to provide the required levels of ventilation. Are current design practices adequate to achieve these ventilation requirements? Once a building and its ventilation system have been designed and installed, how is it actually operated and maintained and, as a result, how much outdoor air is being provided to the occupied spaces of a building? The last question leads perhaps to an even more important one; how well can we measure building ventilation rates for research purposes and for use in regular building operation and maintenance?

Given the energy required to transport, heat and cool ventilation air, can we continue to use current mechanical ventilation approaches as the world's energy resources become increasingly scarce and as the pressures of global warming impact energy policy? Can natural or passive ventilation systems be used to address these environmental concerns and still provide reliable ventilation rates?

It is not surprising that an issue as important as ventilation is associated with so many questions. However, it is surprising that the existence and importance of so many of these questions are not always appreciated, let alone answered.

2. Science Supporting Ventilation Requirements

The primary purpose of outdoor air ventilation is to dilute internally generated contaminants to levels that are not harmful to human health and that do not negatively impact occupant perceptions of the indoor environment. In more positive terms, we ventilate buildings to provide healthful and comfortable, even pleasant, indoor environments. However, indoor concentration limits to meet these goals of health and comfort have not been established. Therefore, we have historically used and continue to use outdoor air ventilation rates as criteria for these goals. Relying on outdoor air ventilation is inherently limited given the wide variation in contaminant emission rates among different (or even the same) sources, and therefore among buildings, and in the susceptibility of different individuals to contaminant exposures. But

due to our limited understanding and control of these emissions rates and occupant responses, we appear to have no choice but to use ventilation criteria that may not meet our desire for quality indoor environments.

2.1 Ventilation and Odour Perception

There have been many decades of research into outdoor air requirements, and the goals of these requirements have evolved over time. Starting in the second half of the nineteenth century, the research focused on the control of odours from human bioeffluents (Klauss et al. 1970). Based on the seminal work of Von Pettenkofer, Saeltzer and Billings, ventilation requirements were determined based on the dilution of bioeffluents. These ideas led to research by Yaglou et al. (1936) in which environmental chambers were used to investigate the ventilation required to control the odour from these bioeffluents. Human subjects were asked to rate odour intensity as a function of the ventilation airflow per person. This research resulted in a recommendation of about 7.5 L/s to 9 L/s per person to dilute body odour to an acceptable level as judged by individuals entering the room from relatively clean air. In addition, this research provided adjustments to these recommendations as a function of socioeconomic status, reportedly due to an association with bathing frequency, a conclusion that would cause many to cringe today.

Since the work of Yaglou, a number of studies have been conducted, both in laboratory chambers and actual buildings, in which individuals rated odour intensity and perceived acceptability with respect to human body odour over a range of outdoor air ventilation rates. These studies investigated odour perception and acceptability as a function of gender and whether the subjects were adapted to odours or had just entered the test space. Figure 1 presents the results of several such studies in the form of plots of percent satisfied with the intensity of body odour versus the ventilation rate per person (Cain et al. 1983; Fanger and Berg-Munch 1983; Iwashita et al. 1990). Note that the upper plot, with higher rates of satisfaction, refers to adapted individuals, while the lower three plots correspond to individuals who made their judgments about odour immediately upon entering the test space. This difference reflects the tendency of people to adapt to body odour in a relatively short period of time, in the order of minutes (Gunnarsen and Fanger 1992). However, such adaptation does not occur for all indoor contaminants. In fact, as discussed below, the

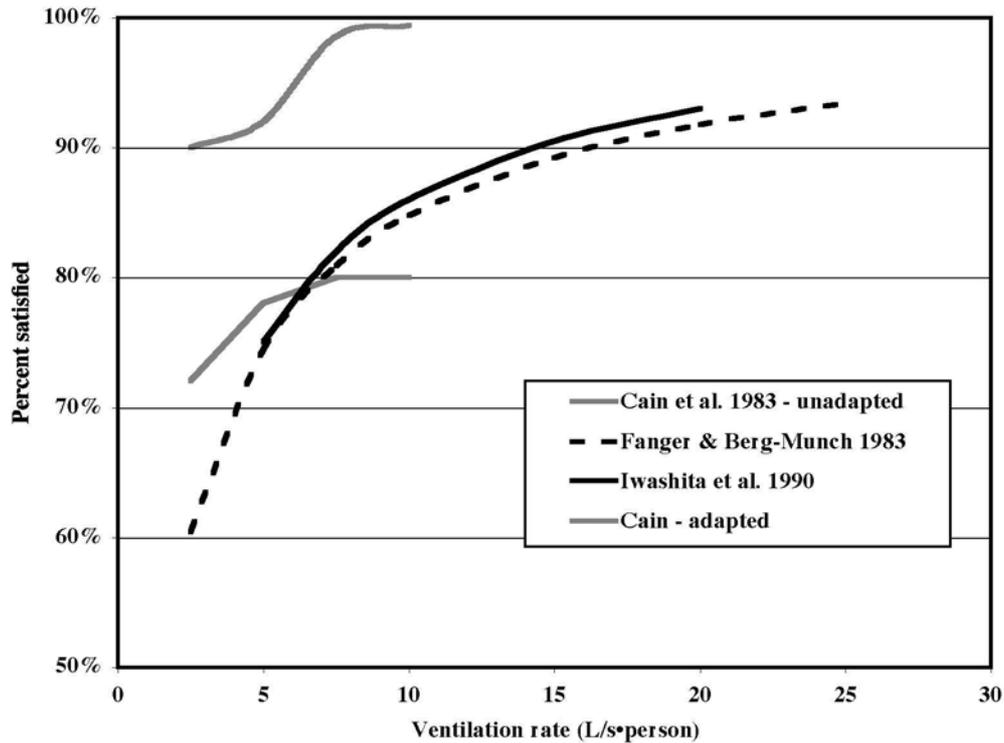


Figure 1. Summary of research on perceived body odour acceptability.

perception of odour and irritation can increase with time for some contaminants. While adapted individuals need less ventilation to achieve similar levels of acceptance based on perception of body odour, the dependence on ventilation rate is less well characterized.

This research on perception of bioeffluents has served as the basis for ventilation requirements in most standards and building regulations. However, it is only one contaminant of many, and not of great concern in terms of human health. How many researchers and practitioners realize that most ventilation standards are based largely on research into the perception of human body odour? ASHRAE Standard 62-1989 (ASHRAE, 1989) is one example of such a standard, and while the standard itself did not present the rationale for the ventilation rates, the committee chair noted that the minimum ventilation requirement of 7.5 L/s•person is based on body odour control (Janssen 1989). This minimum was increased to 10 L/s•person in many building types to account for contaminants other than human bioeffluents, such as building materials and furnishings, though no specific methodology for determining the increase is noted. This acknowledgement of additional sources was a sign of future standards that would focus on contaminant

emissions from occupant activities, building materials and furnishings, and other non-occupant sources. Nevertheless, this and most other standards and guidelines at the time were based largely on control of human body odour. While a single value of the per person ventilation requirement for each space type offers simplicity of application, it assumes that building occupants will on average experience levels of perceived odour acceptability that are the same as those seen in the noted research studies and ignores building-to-building variability in non-occupant contaminant sources. There is also an assumption that this ventilation rate will control contaminants that are imperceptible to human occupants to meet the health objectives of ventilation. While the research data and practical experience do not support building-specific ventilation requirements, the use of requirements that do not recognize the uniqueness of buildings and occupants are inherently limited if not questionable.

While the importance of indoor contaminants beyond human bioeffluents was acknowledged in the 1989 ASHRAE standard, it became more widely recognized as the field of indoor air quality matured in the 1980s and 1990s. During that time, research was pursued to characterize contaminant emissions

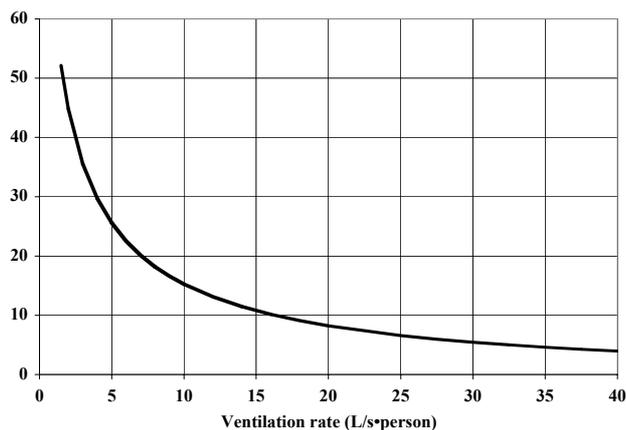


Figure 2. Percent dissatisfied versus ventilation rate per person (CEC 1992).

from building materials, starting with formaldehyde from composite wood products and continuing on to more general volatile organic compound (VOC) emissions from other materials and furnishings (Mølhave 1982; Wallace et al. 1987; Levin 1989; Wolkoff 1995). While this research was not sufficient to serve as the basis for ventilation requirements, it highlighted the need to move beyond bioeffluents as the sole “design” contaminant. To that end, Fanger (1988) proposed the concept of the olf and the decipol as a means to quantify perceived air quality from sources including people, materials and smoking. In this approach, the olf indirectly quantifies the source strength of contaminants that impact perceived air quality; the decipol is defined as the perceived air quality in a space with a pollution source of one olf ventilated with 10 L/s of clean air. Olf values have been associated with occupants as a function of the level of physical activity, with 1 olf being the emissions from a “standard” non-smoking sedentary adult. Figure 2 shows the level of dissatisfaction with the perceived odour intensity corresponding to an “emission” rate of 1 olf as a function of

ventilation rate. The curve in this figure is consistent with the data for unadapted visitors in Figure 1.

Researchers have quantified olfs emitted per m² of floor area in different types of buildings and from tobacco smoking in recognition of the importance of sources beyond human metabolism. Table 1 summarizes measured sensory pollutant loads from materials and furnishings measured in four different building types. These data exhibit a wide variability, covering a range from about 5 to 1 to as much as 50 to 1 for a single building type. Note that these and similar results consider only the sensory load determined with a methodology focused on perception by unadapted and trained subjects and that the results represent an average over many subjects. Note also the absence of any residential buildings in Table 1.

Related research has shown that the olfs from different sources can be summed to determine the total olf load in a space, and therefore the ventilation rate required to achieve a specific level of perceived indoor air quality. The additivity of sources of sensory pollutants has been demonstrated in both laboratory (Iwashita and Kimura 1995; Lauridsen et al. 1988) and field settings (Wargoeki et al. 1996). In these studies, the authors measured the level of perceived indoor air quality from humans and different types of building materials and furnishings alone and in combination. They then compared the total source strength when the sources were combined with the sum of the source strengths of the individual sources. Note that this concept of additivity applies only to contaminants as they impact perceived indoor air quality, and while the agreement was generally good, it was not perfect, as has been noted in other studies (Bluyssen and Cornelissen 1997).

While perceived IAQ (PIAQ) (as measured by the olf) is important, it has limitations. It does not account for the uniqueness of different contaminant

Table 1. Summary of building sensory pollution loads.

	Sensory pollution load (olf/m ² floor)		References
	Mean	Range	
Offices	0.3	0.02-0.95	Fanger et al. 1988, Pejtersen et al. 1990
Schools (class rooms)	0.3	0.12-0.54	Thorstensen et al. 1990
Kindergartens	0.4	0.20-0.74	Pejtersen et al. 1991
Assembly halls	0.5	0.13-1.32	Fanger et al. 1988

sources or of individual contaminants and their unique health and comfort impacts, particularly those contaminants that do not impact PIAQ. A good example of the latter is an odourless but deadly contaminant, such as carbon monoxide. In addition, the methods used to evaluate PIAQ involve judgments of subjects during the first few seconds of exposure, that is, “unadapted” individuals. Individuals who have been exposed to some odours, including body odour, for more than about one minute begin to adapt and lose their sensitivity to the odour (Gunnarsen and Fanger 1992). On the other hand, humans do not adapt to some other odours as quickly, for example tobacco smoke and some building materials (Gunnarsen 1990). Irritation responses may actually increase over time and are not necessarily well captured by judgments made after a few seconds or even minutes of exposure (Cain et al. 1986; Hempel-Jorgensen et al. 1999). Furthermore, these sensory loads and the derived ventilation rates assess the average response of a large number of individuals and do not address those who are more (or less) sensitive.

Nevertheless, research on perceived IAQ in buildings has been used in support of the ventilation requirements for non-occupant sources in the recent revision of ASHRAE Standard 62 (ASHRAE 2004a) and in the CEN indoor environment design criteria (CEN 1998). While these requirements only address sensory perception and oversimplify the complexities of contaminant emissions and differences between apparently similar spaces and buildings, they constitute a significant change by explicitly acknowledging non-occupant contaminant sources.

2.2 Ventilation and Occupant Symptoms

There is another body of research in occupied buildings focusing on symptoms experienced by building occupants, referred to as sick building syndrome (SBS) symptoms, as a function of ventilation rates and other factors. Epidemiological research techniques have been used to identify a number of risk factors associated with these symptoms. Among other factors, this research has noted that increased symptoms tend to be associated with VDT (video display terminal) use, job stress, carpet, and high-density occupancy (Mendell 1993; Sundell 1996). Seppänen and Fisk (2002) also concluded that relative to natural ventilation, mechanical ventilation with air conditioning was consistently associated with a significant increase in the prevalence of SBS symptoms.

Focusing exclusively on office buildings, this research led to the conclusion that, on average, symptoms are more likely to occur for outdoor air ventilation rates below 10 L/s•person than at rates above this value (Mendell 1993). Figure 3 shows the results of a number of these studies as assembled by Seppänen et al. (1999). In this figure, the circles denote the mean ventilation rates compared in each study, with the solid black circles being associated with a significantly higher prevalence of symptoms. The shaded bars indicate the existence of a dose-response relationship between ventilation and symptoms. The results of this study show a higher prevalence of symptoms below 10 L/s•person than at higher rates. This research has been used to support office building ventilation requirements of 10 L/s•person. However, it is important to note that these studies did not necessarily employ the same approaches for determining symptom prevalence or for quantifying ventilation rates, and they generally did not report the uncertainty or the distribution of responses associated with the reported values. Careful examination of these data reveal that at any given ventilation rate, there is a potentially large difference in symptom prevalence. Perhaps understanding these differences is more important than determining the “right” ventilation rates. Note that similar datasets do not exist for the many other types of buildings of interest including educational,

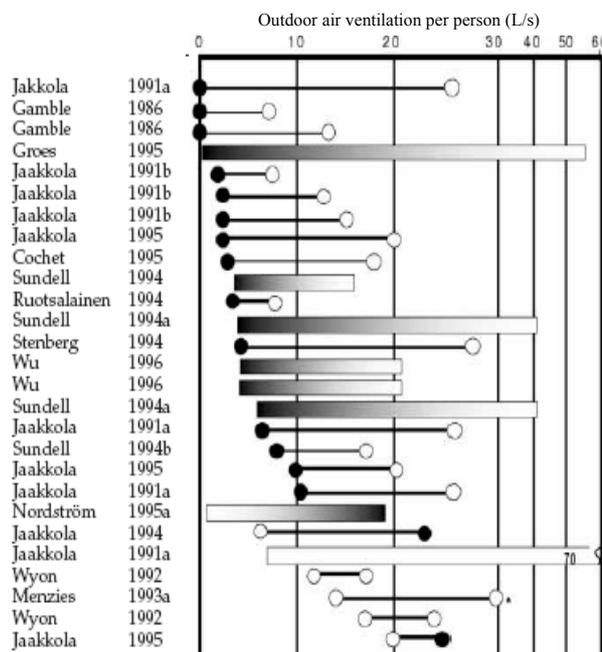


Figure 3. SBS symptoms and ventilation rates in office buildings (Seppänen et al. 1999).

retail, and residential, where one might expect variations in contaminant sources and occupants that are at least as large as in office buildings.

In summary, the science on which we base ventilation requirements includes ventilation rates to control body odour, the perception of non-occupant sources by unadapted individuals, and associations between ventilation rates and SBS symptoms in office buildings. There are clearly gaps in this body of research including, for example, health and comfort impacts of contaminants beyond body odour, differences in these impacts among individuals, and symptom rates as a function of ventilation in buildings other than offices. Nevertheless, standards and guidance are needed to design and operate buildings, even if the science behind them is incomplete and imperfect. Also, as discussed later in this paper, the correlation between ventilation rates in standards and building design and the rates that occur in real buildings has not been established. In fact, it has barely been studied. Perhaps we are spending too much time debating the ventilation rates in our standards and not enough time studying the rates in our buildings.

3. Ventilation Standards and Regulations

As noted earlier, while the primary purpose of outdoor air ventilation is to dilute internally generated contaminants, contaminant concentration limits have not been established for non-industrial environments. Therefore, we use outdoor air ventilation rates as the criteria for indoor air quality in standards and regulations, and subsequently in building and system design. Organizations have been developing building regulations, standards and other documents with ventilation requirements for decades (Janssen 1999; Limb 2001). These efforts have been informed by the research that existed at the time, the collective experience of those participating in the process and of course some politics.

The first ventilation regulations in the United States were issued in the late nineteenth century through legislation in various states and cities, generally with a minimum outdoor air requirement of 15 L/s per person. ASHRAE's predecessor organization, ASHVE, issued a model law in 1894 containing that outdoor air requirement. Subsequent research on body odour perception, discussed in the previous section, led to a lowering of these standards to roughly 10 L/s per person. The first consensus standard in the United States was ASA A53.1, Light

and Ventilation, published in 1946 by the American Standards Association. This standard was replaced in 1973 by the first version of ASHRAE Standard 62 (ASHRAE 1973), which contained both minimum and recommended ventilation rates for over 250 space types. While these ventilation requirements were a major advance at the time, they were not informed by more recent concerns about the broader health and comfort impacts of indoor environments and about the limitations in our energy resources.

The subsequent development of ASHRAE Standard 62 reflected the growing concerns regarding indoor air quality and energy (Stanke 1999). When Standard 62 was republished in 1981 (ASHRAE 1981), indoor air quality was added to the title of the standard for the first time. In addition, the recommended ventilation rates were deleted in favor of minimum rates only, which were, in many cases, reduced significantly in response to energy concerns of the 1970s. For example, the minimum ventilation rate in non-smoking office spaces was only 2.5 L/s per person. The 1981 standard also added the Indoor Air Quality Procedure, an alternative, performance-based design method in which ventilation rates and other design parameters are determined from contaminant concentrations rather than the table of ventilation rates contained in the prescriptive Ventilation Rate Procedure. The addition of the IAQ Procedure, while admittedly challenging to use in practice given the lack of contaminant limits and source strength data, was an acknowledgement of the importance of sources other than occupants and of contaminants other than body odour. In ASHRAE Standard 62-1989 (ASHRAE 1989), the minimum rates were tripled or more relative to the 1981 standard, in recognition that the energy-driven rates in the 1981 standard were too low.

The recent revision of the standard (ASHRAE 2004a) marks the first change in the Ventilation Rate Procedure since the 1989 standard. While the revision retains the minimum approach to ventilation, it contains ventilation requirements based on the number of people and based on the floor area of the space being ventilated. The former still derives from the research on body odour control, but employs the values for adapted individuals given that the standard is intended for code adoption, which in the United States means minimum requirements. This minimum philosophy reduced the per person rates to values as low as 2.5 L/s per person. Perhaps more important, the revision explicitly acknowledges the existence of

non-occupant contaminant sources by also including a ventilation requirement per unit floor area. This requirement is based largely on the work on perceived indoor air quality due to building-related sources, some of which was summarized in Table 1. In determining the ventilation requirement of a space, the per-person requirement is multiplied by the number of people and added to the floor area multiplied by the building requirement. Given typical occupant densities, the total per person requirement for most spaces (after adding in the building requirement) is similar to the requirements in the 1989 standard. The only significant reductions occur in densely occupied spaces such as conference rooms and assembly halls. While the new Ventilation Rate Procedure falls far short of providing building specific ventilation requirements, it is a significant advance. However, the requirements in the standard are still based largely on odour perception and on average responses rather than the more sensitive building occupants. These requirements have resulted from a compromise between those who want lower rates based primarily on energy cost concerns and those who call for higher rates based on evidence that more outdoor air reduces occupant symptoms.

The ASHRAE committees responsible for the various versions of Standard 62, and other standard development bodies, have had to deal with a range of issues including the adequacy of the technical bases for the ventilation requirements, whether they should target adapted occupants or unadapted visitors, and whether they were developing minimum requirements or recommendations. In addition, the ventilation requirements in these documents generally apply to the occupied or breathing zone of a space, and adjustments are required to account for air distribution inefficiencies. Standard 62 has dealt with this latter issue through air distribution effectiveness to account for non-uniform distribution in the ventilation space and system efficiencies to account for inefficiencies inherent in multiple-zone recirculating systems. These adjustments can, in effect, convert a 10 L/s•person ventilation requirement in the breathing zone to a higher value when considered at the building outdoor air intake. At the same time, innovative air distribution techniques such as task ventilation and some displacement strategies may allow reductions in the per person rates brought into the building.

Ventilation standards have progressed over the years from focusing almost exclusively on body odour

control to the consideration of non-occupant contaminant sources. Their technical soundness and practicality has also improved based on the accumulation of new research results and practical experience. Nevertheless, the ventilation requirements in these standards do not account for the differences among buildings and the occupants, materials and activities within them. Developing ventilation requirements that account for these differences will require a significant amount of research on human response to specific contaminants and contaminant mixtures as well as emission rates from various materials and activities. The time and resources required to conduct this research may be beyond the resources available to the indoor air quality community, and it may not even be worth the effort.

4. Ventilation Design

Ventilation design for IAQ should be based directly on the control of contaminant concentrations for health and comfort. This approach would be analogous to structural and thermal design, with contaminant sources strengths treated as loads. However, the current lack of contaminant limits and insufficient data on emission rates leads to the use of ventilation rates as the design criteria. There are two primary design issues related to ventilation performance in buildings: determining design outdoor air ventilation rates, and then selecting and configuring a system that will reliably achieve these rates at a reasonable level of cost and energy consumption. The first issue should be relatively straightforward given the proper application of the relevant standards and regulations. These ventilation design calculations are typically done when heating and cooling load calculations are performed to size space conditioning equipment, since ventilation rates are needed to determine these loads. After the outdoor air requirements are determined for the individual zones, they need to be related to the total outdoor air of the ventilation system serving the zones. The system outdoor air intake is needed to size the system heating and cooling capacity. Relating zone requirements to system outdoor air intake involves adjustments for room air mixing (sometimes referred to as air change or ventilation effectiveness, or zone air distribution effectiveness) and distribution efficiencies in systems that recirculate return air to and from multiple zones. ASHRAE Standard 62 describes how to relate zone ventilation requirements to system intake. Other standards and building regulations contain only

outdoor air requirements for individual spaces or zones and do not address system outdoor air intake. Note that while the ventilation rates to the occupied zones are most relevant to indoor air quality, they are extremely difficult to measure in the field, making it impractical to verify that the design intent has been realized. The measurement of system intake rates is more straightforward.

The second major design issue, system selection and configuration, has a much broader scope and is critical to achieving good ventilation performance. These decisions include the type of system, the control strategies and the air distribution approaches that will be used to heat and cool the building, while simultaneously providing the required ventilation rates over the range of outdoor weather and interior loads that are expected to occur. Maintaining the design outdoor air ventilation under the range of conditions can be challenging, but must be part of the design strategy with particular attention given to operation under part load and other non-design conditions. Note that these system options include natural or hybrid (mixed-mode) ventilation in addition to strictly mechanical ventilation approaches. Other design approaches of current interest include task and displacement air distribution strategies that provide ventilation air more directly to the occupants, demand controlled ventilation using CO₂ and other indicators of occupancy to reduce ventilation and therefore energy consumption during periods of low occupancy, and various heat recovery options.

Natural and hybrid ventilation approaches are receiving attention as part of sustainable building strategies to reduce energy consumption in buildings (Axley 2001; CIBSE 1997). In addition, as noted earlier, building occupants tend to prefer indoor environments with natural ventilation relative to mechanically ventilated buildings. The reasons for this observed preference are not understood, due to the general lack of contaminant concentration and ventilation rate measurements in these studies. Natural and hybrid approaches also have the potential to reduce energy consumed for heating, cooling and moving air, but they have their own design challenges including locating and sizing air inlets and exhausts, addressing variations in weather-induced pressures on which they rely, and poor outdoor air quality. Many proponents of natural ventilation do not necessarily appreciate or understand these design issues and assume that natural ventilation is good in and of itself without examining the outdoor air ventilation rates that the

system actually provides, particularly during mild weather. In fact, these systems sometimes appear to be designed based more on aesthetic considerations and wishful thinking regarding ventilation rates and air distribution rather than engineering principles. Engineering methods and design tools do exist (Dols and Emmerich 2003), but they are not widely used in practice. Some notable exceptions do exist where sophisticated CFD analysis has been done to inform design of natural and hybrid systems. Nevertheless, as energy resources become scarcer and environmental concerns related to fossil fuel consumption increase, more energy efficient ventilation approaches such as natural and hybrid ventilation become more attractive, if not essential.

In addition to outdoor air ventilation rates and system selection, there are other critical design issues that are often not part of regulations or sometimes not adequately addressed in practice. These include access to system components for testing, inspection, calibration and maintenance, such as dampers, coils, filters, and temperature and humidity sensors. In addition, systems and ductwork needs to be configured to allow reliable velocity traverse measurements for system commissioning and maintenance throughout the life of the building by providing sufficiently long duct runs and access to the ductwork. Finally, it is critical to document the design assumptions related to the ventilation system (including the thermal loads) and to transmit this documentation to the building owner and operator.

Residential buildings, particularly low-rise dwellings, have different design issues from the commercial and institutional buildings that have been the focus of much of the preceding discussion. The occupancy levels and the indoor furnishings and activities in residential buildings are much less predictable at the design stage. Residential buildings have traditionally been ventilated by envelope infiltration at rates determined by the building airtightness, which is typically not a design parameter. Standards do contain outdoor air ventilation requirements for residential buildings, but these have not generally been used in building design. More recently, mechanical ventilation has been used in residential buildings to achieve these design ventilation rates and this trend is expected to continue as buildings become tighter, as IAQ awareness increases and as energy efficiency improvements such as heat recovery become more essential.

5. Ventilation System Operation, Maintenance and Performance

Even if the ventilation requirements in standards and building codes were 100 % sound from a technical perspective, and even if the outdoor air intake were uniquely determined for each building, and even if the system were designed, installed and commissioned as intended, the question remains: How will the system perform over time? Specifically, how much outdoor air will be brought into the building and be delivered to the various spaces? Given that ventilation requirements, design and construction practice are imperfect, the question of actual performance becomes even more challenging. While operation and maintenance (O&M) are critical to many aspects of building performance, they generally do not receive the attention and resources they merit. The reasons include a lack of awareness of their importance and a lack of financial commitment, even though economic arguments exist for good O&M based on reduced energy consumption and increased occupant productivity (Fisk and Rosenfeld 1997). Fortunately, the importance of O&M is receiving increasing attention; for example, ASHRAE has recently started the development of a standard practice for the inspection and maintenance of HVAC systems (ASHRAE 2004b).

The most critical operational issues for ventilation systems are simply operating them based on building use and occupancy schedules and not taking actions to defeat the system. While the former sounds straightforward, it becomes more critical when occupancy patterns change relative to the assumptions on which the design is based, in which case the operating schedules and perhaps the ventilation rates themselves may need to be adjusted. Examples of actions that defeat system operation include closing outdoor air intake dampers as an ill-conceived energy conservation effort or turning systems off to “save” energy or in response to noise complaints. Most mechanical ventilation systems operate on time schedules and modulate airflow in response to indoor and outdoor temperature and humidity conditions. Natural ventilation systems generally require more “hands-on” operation, in some cases requiring building personnel, even occupants, to manually open and adjust vents. Similarly, recent trends towards task ventilation systems with individual supply air outlets located in occupant workspaces present operational responsibilities to the building occupants. In fact, studies have shown that

occupants rate indoor environments higher when they have control of ventilation (Arens et al. 1991). Proper operation of both natural and task ventilation systems requires occupant education. Good performance of any type of ventilation system also requires regular inspections and routine maintenance of system components. The details of which components to inspect and maintain depend on the specific system type and design but generally include outdoor air intakes, temperature and humidity sensors, dampers, and filters. In addition to system maintenance, overall building maintenance in terms of cleanliness, prompt attention to water leaks, and other potential contaminant sources is also critical.

Given all the discussion and debate of ventilation requirements and system design strategies, there are surprisingly few measurements of actual ventilation performance in buildings, and the measurements that do exist reveal discrepancies between system design and performance. One of the earliest papers on the office building ventilation rates in the U.S. found that about one-half the 3000 measurements in fourteen US. office buildings were below 10 L/s•person and about half were also below the buildings design specification for minimum outdoor air intake (Persily 1989). Other measurements support the conclusion that system airflow rates can be quite different from design values and lead to undesirable consequences related to IAQ, energy use and moisture management (Cummings 1996).

The U.S. EPA Building Assessment Survey and Evaluation or BASE study is a more recent source of measured ventilation rates (EPA 2003). The primary goal of the EPA BASE study was to define the status of the existing U.S. office building stock with respect to determinants of IAQ and occupant perceptions. The study involved one week of measurements in 100 randomly selected office buildings using a protocol incorporating three study areas: comfort and environmental measurements, building and HVAC characterization, and an occupant questionnaire. The ventilation data from the study was recently analyzed and demonstrates the discrepancy between design and performance (Persily and Gorfain 2004). For example, Figure 4 displays the values of the ratio of the measured outdoor air intake to the design intake under conditions of minimum outdoor air. (Note that of the 141 ventilation systems investigated in the study, design minimum outdoor air intake values were available for only about half.) A value of one corresponds to a measured minimum outdoor

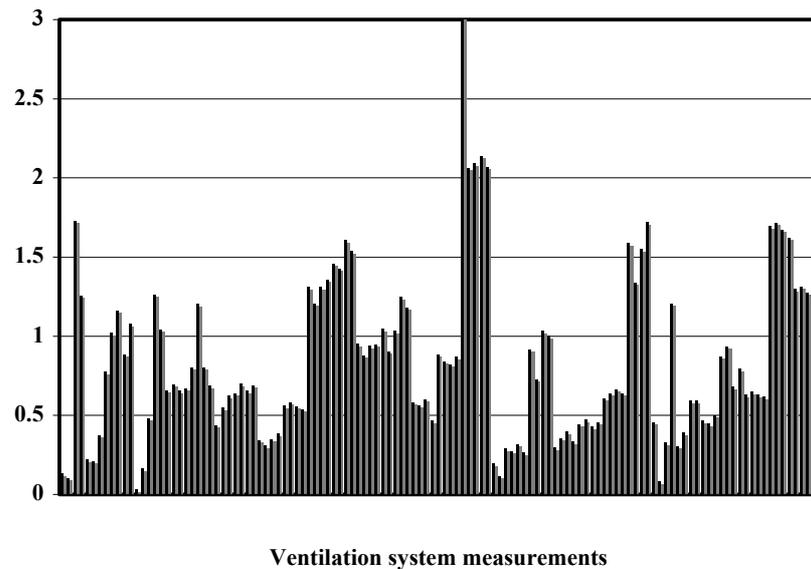


Figure 4. Ratio of minimum measured to design outdoor air intake from EPA BASE study.

airflow equal to the design value. The mean ratio of the measured to design outdoor airflow under minimum intake is 0.85, and the median value is 0.69. However, there are many values of the measured-to-design ratio that are well below one, indicating less outdoor air intake that intended.

The ventilation data collected in the BASE study, and other studies, demonstrate that design values of outdoor airflow rates, as well as other aspects of ventilation system performance, are not necessarily realized in practice. Presumably inadequate O&M is behind much of this discrepancy, and bringing performance closer to design will require a commitment beyond current practice.

While residential buildings are not generally designed to achieve a specific outdoor air ventilation rate (at least when infiltration is the source of ventilation air), there have been more measurements of ventilation in residential buildings than in commercial buildings. Most of the residential building studies have involved only a small number of homes, which do not provide an indication of trends in residential building ventilation and cannot be generalized to other buildings. One particular dataset of about 4000 measurements in U.S. homes is particularly noteworthy (Pandian et al. 1998), but it employed a passive injection, long term sampling tracer technique that, as described in the next section, is associated with a significant measurement bias. In addition, the homes in the survey did not constitute a representative sample.

Nevertheless, this study reveals variations by region (associated with climate) and season, which is not unexpected given the strong dependence of infiltration on weather. Much more data are available on residential building airtightness, for example a dataset of 12000 measurements in U.S. dwellings (Sherman and Dickerson 1998). This study reveals a trend towards tighter homes in more recent years, but the variation is extremely large, limiting expectations regarding the tightness of an individual home based on its age. Also, the relationship of airtightness values to ventilation rates is a strong function of weather conditions, window and door opening patterns, and system operation (Concannon 2002), and prediction of ventilation rates from airtightness, while possible, is not very reliable.

More detailed studies of smaller numbers of homes, often involving simulation, have shown that envelope infiltration is not a reliable means of ventilating buildings (Persily 1998 and 2000). Even in leaky buildings, infiltration rates will be quite low under mild weather conditions. Mechanical ventilation systems can provide reliable ventilation in residential buildings, i.e., relative to the ventilation rates in standards (Mansson 1995; Matson and Feustel 1997). However, as noted earlier, residential buildings probably have a wider variation in contaminant source strengths, and the requirements in the standards are not likely to apply to all residential buildings. O&M is still critical in residential buildings, and perhaps more challenging than in

commercial buildings given the limited expertise of the individuals responsible for these systems.

6. Ventilation Measurement

Building ventilation rates have been measured for many decades using a number of different methods, and much experience has been obtained in the application of these methods. While technical advances have improved the performance and reduced the cost of instrumentation, the reliable determination of ventilation rates is still quite challenging in the field. In the context of indoor air quality, the quantities of most interest are whole building air change rates, ventilation system outdoor air intake, and outdoor air delivery to specific spaces or zones in a building. Whole building air change rates are the sum of the system outdoor air intake and air infiltration through envelope leakage. The latter is often assumed to be negligible, but in fact commercial buildings have been shown to be quite leaky (Persily 1999), with no evidence that new buildings are tighter than old buildings. As a result, to the first order, infiltration rates in mechanically ventilated commercial buildings can be assumed to be equal to intentional outdoor air intake rates.

Tracer gas measurement methods provide the only means to determine whole building air change rates. The only practical methods for doing so consider the building as a single zone, i.e., with sufficient mixing such that the tracer gas concentration is roughly uniform throughout the building (ASTM 2000). When using these single zone techniques, uniform tracer concentrations must be established through multipoint measurements. However, these single-zone methods provide only whole building air change rates and no information on outdoor airflows to individual rooms. It is important to note that a tracer gas decay rate measured in a single zone is not the outdoor air change rate of that zone unless interzone effects can be ignored, which is generally not the case. Even after more than 50 years of single zone tracer decay measurements, researchers still make the mistake of interpreting the decay rate in a room as its outdoor airflow rate.

Tracer gas techniques do exist to characterize building airflows where multizone effects are important, but these methods are largely in the realm of research, have not yet been standardized, and do not lend themselves to application in IAQ surveys or field studies. Even single-zone tracer gas methods require a significant level of expertise to

produce reliable results, and typical field measurements generally have measurement uncertainties no better than $\pm 20\%$ and can be much worse. For some methods, such as long-term tracer injection with average concentration sampling (sometimes referred to as the PFT method), the errors can be larger and measurement biases are known to exist (Sherman 1989). Even with the most reliable measurements, it is critical to understand that whole building air change rates vary considerably due to weather and system operation effects, easily over a range of 5 to 1 or greater, and that a single measurement is not sufficient to characterize ventilation in a given building. When a single air change rate value is reported for a building with no indication of the weather conditions or the time period over which it might have been averaged, the value is not a useful indicator of the building's ventilation characteristics.

The determination of outdoor air intake rates at system intakes generally relies on traditional air speed traverse methods (ASHRAE 1988). However, these techniques require a sufficiently uniform velocity profile across the duct cross-section where the traverse takes place as well as adequate access to the duct. Both of these are a function of the layout of the duct system, with the former requiring sufficiently long lengths of ductwork to establish uniform velocity profiles, which often do not exist in buildings. Other airflow measurement methods exist to determine system outdoor air intake, such as multi-point hot-wire anemometer arrays and dampers designed with pressure taps to determine the pressure difference across the damper, which in turn is related to the outdoor airflow via a calibration. However, these techniques can still be impacted by non-uniform velocity profiles and are not in wide use. Finally, while these traditional traverse measurements have been used for decades, the measurement uncertainties in the field have never been characterized.

Outdoor air delivery to individual rooms, or the occupied areas within rooms, is of particular interest when interpreting contaminant exposure and occupant symptoms. However, these quantities are extremely difficult to determine without employing fairly advanced tracer gas measurement methods, such as age-of-air, that are not widely used in field studies. Alternatively, one can measure airflow rates from the supply air outlets serving the room of interest using flow hoods and other more traditional measurement methods, assuming one knows the outdoor air fraction (i.e., the ratio of outdoor air to

supply air) in the supply airstream. However, measurements at the outlet neglect outdoor airflow into the space via adjacent zones and envelope infiltration. As noted above, tracer gas decay rates in individual rooms do not equal outdoor airflow rates, unless interzone airflows can be neglected. Some have used indoor carbon dioxide (CO₂) concentrations to estimate outdoor airflows within rooms. However, while widely used, this approach is not generally reliable as noted below.

Naturally ventilated buildings pose a particular challenge to existing ventilation measurement techniques. Single-zone tracer techniques can in theory be employed, however given the non-mixing air distribution patterns common in these buildings and the existence of large openings in exterior walls, it is unlikely that the tracer concentration in the building will be sufficiently uniform. There is some data on whole building and individual room ventilation rates in naturally ventilated buildings. Most of this has been obtained using single-zone mass balance analysis based on indoor carbon dioxide (CO₂) concentrations (Coley and Beisteiner 2002, Roulet and Foradini 2002) or passive, constant injection tracer methods (Stymne and Boman 1996). As noted, these techniques can be associated with significant measurement uncertainty.

Occupant-generated CO₂ has long been advocated as a means of estimating building ventilation rates, despite analysis and guidance identifying important limitations to its use (ASTM 1998, Persily 1997). This approach generally employs a single-zone mass balance of CO₂, in most cases assuming that the concentration is at equilibrium. In addition, the method assumes constant CO₂ generation (i.e., constant occupancy and activity), outdoor concentration and ventilation rate. And since the methods employ a single-zone mass balance, the CO₂ concentration must be sufficiently uniform throughout the entire building. Therefore, carbon dioxide concentrations in individual rooms or occupied space locations cannot generally be related to outdoor air ventilation rates.

7. Discussion and Conclusions

The amount of outdoor air required in and actually provided to buildings has not received the attention that it merits, and in many ways we know very little about either. It is important that the IAQ and building HVAC communities acknowledge the

limitations of what we do know, and perhaps will ever know, about how much outdoor air is needed in buildings. Nevertheless, standards are needed that contain outdoor air requirements, and these standards need to be taken seriously in design and operation. It is also important when using these requirements, to recognize that minimum requirements are minimums and not recommendations. Beyond providing adequate amounts of outdoor air, systems also need to be designed to facilitate inspection and O&M by providing space to access system components and configuring the system to facilitate reliable airflow measurements.

In terms of the scientific basis for ventilation requirements, more research is needed to make the requirements in our standards more technically sound and more building specific. These research needs include a better understanding of IAQ perception as a function of building type and occupant characteristics. In order to move towards building specific ventilation requirements, we also need research on health and comfort impacts of contaminants that will lead to concentration limits, and better understanding of contaminant sources and impacts of IAQ control technologies. This research agenda is quite ambitious, and it is fair to ask whether this work could be done in any realistic timeframe and whether it should be done. Current research efforts are inadequate to cover all these issues. Rather than expending our limited time and resources on these research questions that may refine ventilation requirements, it might be better to address the disconnect between design intent and building performance by focusing on the chain of design, installation, commissioning, operation and maintenance. When considering this process as a whole, it is not at all clear that the ventilation requirements themselves are the weakest link. While research could better define these requirements by maybe +/- 25 %, or perhaps even more, these other links are currently having impacts in the 100 % range and could be addressed today without waiting for the results of major research efforts. There is no doubt that we need to obtain more building performance data and develop more reliable measurement methods, but a great deal of improvement in the ventilation of building environments could be realized today through a commitment to building and system operation and maintenance.

While ventilation measurement is difficult and not terribly accurate in the field, it is essential in our

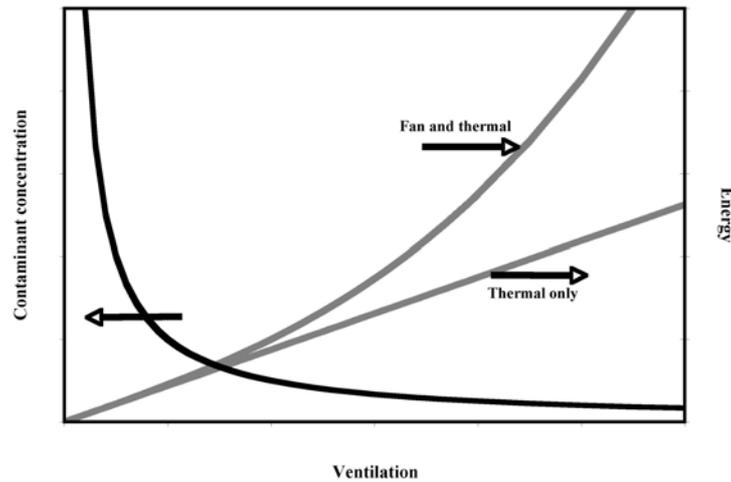


Figure 5. Dependence of concentration and energy on ventilation.

efforts to achieve better ventilation performance to ensure occupant comfort and health or to avoid wasteful use of energy. Despite the suggestion that we should be focusing less on quantifying ventilation requirements, it is critical that IAQ studies address the impacts of ventilation rates on indoor contaminant concentrations. And when doing so, reliable measurement methods must be employed and the results must be presented with the associated measurement uncertainties. Whatever technique is used, the assumptions on which it is based must be examined in the given application. In particular, extreme care must be exercised when using indoor CO₂ concentrations to estimate ventilation rates and when attempting to characterize outdoor air delivery rates to individual rooms. The same holds true when reading and interpreting IAQ studies that report ventilation rates. We all need to be more diligent in assessing the ventilation measurements methods employed, and be particularly wary of CO₂-based values and individual room rates.

Finally, given the energy impacts and the tremendous growth in construction and the application of air-conditioning, we need to be thinking more about energy efficient technologies to achieve the required rates, including heat recovery ventilation, natural and hybrid ventilation, efficient air distribution methods, and interior load reductions. Global environmental pressures are making this increasingly necessary. Figure 5 shows the relationship of steady-state contaminant concentrations and energy to ventilation. Note that the thermal energy associated with ventilation

increases linearly with ventilation rate, while contaminant concentrations decrease in an inverse fashion. Therefore, as ventilation rates increase, the concentration decrease becomes proportionally less while the energy consumption continues to increase at the same rate. The figure also includes an energy curve that includes fan power, which increases with the cube of airflow. This curve highlights the even greater impact for mechanical ventilation systems and the need to pursue non-mechanical ventilation strategies in response to energy and environmental pressures.

Despite the importance of ventilation in the context of IAQ and energy, it is poorly understood in many respects. While we have been and may continue to debate how much outdoor air is needed in buildings and how it impacts indoor contaminant concentrations, we need to devote more effort to designing, installing, operating and maintaining ventilation systems that deliver outdoor air to the building occupants in a more reliable manner than they do now. Fortunately, significant improvements in building ventilation can be made without a major research program but rather by devoting our resources to better building practice. The result will be better IAQ and a more secure energy future.

Acknowledgements

The author wishes to express his appreciation to Steven Emmerich, Hal Levin and Dennis Stanke for their helpful comments on this manuscript.

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